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AT ELEVATED TEMPERATURES
UNDER IMPACT WITH A BOUNCING BALL

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Abstract

This report describes an investigation into the behavior of metals under impact at elevated temperatures. In a series of tests, a hard spherical ball strikes the flat surface of a massive specimen, which in one instance was a commercially pure lead and in another an aluminum alloy. Tests were made at a number of temperatures at each of which the velocity of impact and the velocity of rebound were measured, as well as the size of the permanent indentation in the specimen surface, and the time of contact between ball and specimen. Through dimensional analysis, relations were derived which predict quite accurately the time of contact and the diameter of the permanent indentation for a given material. Following Tabor, energy was used to compute the dynamic yield pressure; and the present investigation offers a further understanding of this quantity. In addition the experimental results are in agreement with the work of both Raman and Davies, who showed that an extremely low impact velocity is needed for impact to be entirely elastic. Finally, present results indicate a possibility that impact tests can be used to measure the dynamic yield stress, but a more complete investigation of this question is reserved for a later report.

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I. **Introduction.**

In a common type of dynamic hardness test, a small but hard indenter is allowed to fall under the action of gravity onto a massive specimen. It is usual to measure the height of drop and either the height of rebound or the size of the indentation remaining in the specimen. Martel, for instance, defined "dynamic hardness number" as the ratio of the energy of the indenter immediately before impact to the volume of the indentation \[1\] *. This ratio has the units of a stress. Shore, on the other hand, used the height of rebound as a measure of hardness, keeping the height of drop constant \[2\].

Many other investigators have performed hardness tests of this type. One might mention the work of Raman \[3\], who measured the coefficient of restitution as a means of gaging the extent of elastic recovery over a range of impact velocities.

Although hardness tests by means of a bouncing ball are easy to perform, the difficulties arise in the interpretation of results. Whereas one can easily define dynamic hardness in terms of measurable quantities, it is considerably more difficult to relate these quantities to properties of the specimen material such as, for instance, the yield stress or the Young's modulus. To do this it would be necessary to have a detailed analysis of the impact process. It is evident, however, that this process is extremely complicated so that even the most thorough analyses as, for instance, those of Andrews \[4,5,6\] and of Tabor \[7\] are necessarily based upon

\* Numbers in brackets refer to the bibliography at the end of the paper.
a number of assumptions. Andrews, in investigating the collision of two spheres of soft metal, assumes that the process includes three stages. The impact starts with an elastic deformation which obeys Hertzian theory. As soon as the yield pressure $p_0$ is reached, a circular plastic region will form over which the pressure is constant and equal to $p_0$. This region enlarges under further forward motion of the spheres while the remaining outer annular region of the area of contact remains elastic. Finally, the spheres stop their approach and start moving apart under an elastic action of the entire deformed contact area. Tabor, in considering the problem of a comparatively hard ball striking a massive flat specimen, neglects the elastic action of the first two stages. On the basis of an energy analysis, he obtains a "mean yield pressure", $P_d$, for the plastic portion of the impact process and a mean pressure at the beginning of the elastic recovery stage, $P_r$. Experimentally, he found that the values of $P_r$ are lower than those of $P_d$ and closer to the yield pressure obtained in static hardness tests. Tabor argues that viscous effects in the specimen are responsible for this difference in the values of $P_d$ and $P_r$. These two analyses, i.e. those of Andrews and Tabor, furnish the best available physical description of the impact process and one satisfactory from a qualitative point of view. The predicted values of time of contact during impact, of the diameter of the permanent indentation, and of the coefficient of restitution, while not in close quantitative agreement.
with experimental results always tend in the right direction.

Crook [8] used a piezo-electric crystal to measure the total force throughout the duration of the impact process. He found that the pressure between the impacting bodies is very nearly constant up to the maximum force and that the magnitude of this pressure is nearly equal to that of Tabor's $P_d$. There is, in addition, further plastic deformation beyond the point of maximum force before the unloading of the specimen becomes entirely elastic. Crook maintains that the difference between the values of $P_d$ and $P_r$ cannot be due to viscous effects as was suggested by Tabor. His argument is that if the mean pressure between the bodies were dependent on the viscosity of the specimen then this pressure would have to vary with the rate of strain, whereas his tests indicate it remains substantially constant while the rate of strain starts at a high value and then goes decreasing. As further evidence, Crook cites the very careful tests of Davies [9], who found that the threshold of plastic deformation occurs at a very low impact velocity, but that even under these conditions in which viscous effects must be small, the pressure acting on the indenter is higher than the static yield pressure of the specimen material.

Raman [3] measured the coefficient of restitution in the impact between two small identical balls, each suspended as a pendulum. The materials tested were copper, aluminum and lead, all at room temperature. His results show an increase
in the value of the coefficient of restitution, \( e \), as the
impact velocity is decreased. Raman was able to decrease the
impact velocity until it was just low enough for \( e \) to equal
unity for copper and for aluminum. Practical limitations
prevented measurements at lower velocities. For lead his
highest value of \( e \) was about 0.80.

The present experiments were undertaken for two reasons:
first, because the results of ball drop tests lie within a
range of strain rates not easily covered using propagating
waves and, secondly, because of the ease with which these tests
can be performed whether the specimen be at room temperature
or at an elevated temperature. Previous work at elevated
temperatures using a dropping ball (e.g. Lea [10], Sauerwald
and Knehans [11]) was concerned mainly with obtaining the
dynamic hardness numbers of various materials. Our general
plan was to investigate the ball drop test as such, and in
particular, to see how results are affected by the temperature
of the specimen. For this purpose the work of previous inves-
tigators was studied and, in some instances, extended. In
addition, it was found that dimensional analysis leads to
relations between the measured quantities which predict quite
accurately experimental results. Finally, we wished to
examine the possibility of using ball drop tests to obtain a
more general understanding of the behavior of materials.
Unfortunately, one is limited experimentally in this respect,
in that for the materials tested it is almost impossible in
a simple set-up to attain a low enough velocity for a purely
elastic impact [3,9]. On the other hand, there is apparently a possibility that the results can be interpreted so as to give values of the dynamic yield stress of the material at different strain rates. While referred to below, this last subject is in the main reserved for a later investigation.

II. Analysis of Impact Process.

(1) Coefficient of restitution.

The coefficient of restitution, $e$, can be defined as the ratio of the magnitude of rebound velocity to velocity of impact. For the bouncing ball tests the work of Hunter [12], of Rayleigh [13], and of Banerji [14] has shown that the amount of energy going into elastic waves within the solid, into vibrations of the indenting ball, or into sound waves, is small, so that nearly all the energy dissipated goes to the formation of a permanent indentation. As a result, the coefficient of restitution provides a qualitative description of the mechanical behavior of the material of the specimen, e.g. entirely elastic when $e = 1$, entirely inelastic when $e = 0$. A set of curves showing the dependence of the coefficient of restitution on impact velocity $v_1$ and on the temperature of the material is useful from this point of view. In particular, any sharp changes in the slope of the $e-v_1$ curve should reveal, in general, a transition from one dissipation mechanism to another or to elastic impact. It would be of interest, for instance, if one could compare lead at room temperature to
other metals at an elevated temperature by finding in both instances the transition from elastic to inelastic impact. Unfortunately this is not possible with the simple set-up used in the present tests because one can never achieve quite low enough velocities to obtain an entirely elastic impact.

(2) Tabor's analysis.

The assumption of elastic-perfectly plastic action in the impact process, i.e. flow with a constant dynamic yield pressure, seems justified on the basis of the results of Tabor's and Andrews' experiments. It is not clear, however, how one can calculate the magnitude of this yield pressure. The first investigator to study the problem was Martel [1], who suggested that the yield pressure be computed from the relation

\[ P_d = \frac{W_1}{V_a} = \frac{mg \cdot h_1}{V_a} \]  

(1)

for a ball of diameter \( D \) dropped from a height \( h_1 \). In this expression \( W_1 \), \( m \), and \( g \) denote respectively the total energy of impact, the mass of the ball, and the acceleration of gravity. \( V_a \) is the apparent volume of the permanent indentation, that is, the volume computed from the observed indentation diameter \( d \) and assuming that the radius of curvature of the indented surface is equal to that of the impacting ball. If \( r_1 \) and \( r_2 \) stand, respectively, for the radius of curvature of the ball and of the permanent
indentation, then

\[ V_a = \frac{na^4}{4r_1} \]

where \( a = \frac{d}{2} \), whereas the actual volume of the indentation is nearer

\[ V_r = \frac{na^4}{4r_2} \]

It is evident, of course, that Hartel does not make use of the energy of rebound. Furthermore, in computing the indentation volume he neglects the elastic recovery. As a result of this recovery, the radius of curvature of the indentation \( r_2 \) exceeds the radius of the ball, \( r_1 \). Tabor [7] suggests that the total energy loss and the actual volume of the permanent indentation be used in computing yield pressure, giving

\[ P_d = \frac{W_1 - W_2}{V_r} = \frac{mg(h_1 - h_2)}{V_r} \]

where \( h_2 \) is the rebound height.

To relate \( r_2 \) to \( r_1 \), Tabor assumes that the rebound process takes place entirely elastically starting with a ball of radius \( r_1 \) in a spherical seat of radius \( r_2 \). Moreover, he takes \( P_d \) as the mean pressure at the instant when the two bodies have a maximum diameter of contact, \( d = 2a \). Using Hertz' theory [15] to equate the elastic strain energy of the recovery process to the rebound velocity of the ball indenter,
he obtains

\[ P_d = \frac{mg}{V_a} \left( h_1 - \frac{3}{8} h_2 \right) \]  \hspace{1cm} (2)

which may be compared to Martel's relation (1) above. Clearly
the difference between (1) and (2) depends on the height of
rebound; and for small \( h_2 \) the results are not very different.

Alternatively, looking only at the rebound process,
one finds for the mean yield pressure \( P_r \) on the basis of
Hertz' theory [15]

\[ P_r^2 = \frac{10}{3} \frac{mgh_2}{V_{a^2}} \left[ \frac{1-\nu_1}{E_1} + \frac{1-\nu_2}{E_2} \right] \]  \hspace{1cm} (3)

where \( E_1, \nu_1 \) and \( E_2, \nu_2 \) are, respectively, the
Young's moduli and Poisson's ratios of ball and specimen.

Tabor compares values of \( P_d \) and of \( P_r \) computed
on the basis of Equations (2) and (3), respectively, to the
value of the static yield pressure \( P_s \) needed to produce
an impression of the same diameter as in the corresponding
impact test. He found first that \( P_s \) is always less than
either \( P_r \) or \( P_d \). Furthermore, \( P_r \) nearly always remains
equal to about 1.1 \( P_s \), whereas the ratio \( P_d/P_s \), while always
above 1.1, is greater the softer the metal. Tabor attributes
this difference in the relative magnitude of \( P_d \) and \( P_r \)
to the viscous effects present in the softer metals. Inelastic
effects, whether time dependent or not, must occur almost
exclusively during the loading process, i.e. as the ball is
moving down. Their presence, therefore, may influence the value of $P_d$. Rebound, however, is largely elastic; and rebound height is determined by the pressure between the ball and the specimen at the start of the rebound process. It can be expected that this pressure will depend almost entirely on the yield stress. Tabor's conclusion, therefore, is two-fold: first, that $P_r$ will be always nearer $P_s$ in magnitude, and second, that $P_r$ will be influenced mainly by plastic (i.e. time-independent) effects as opposed to viscous effects. This means not only that the ratio $P_d/P_r$ will always exceed unity, but that it will increase as viscous effects become more important. This conclusion was borne out by Tabor's results.

(3) Crook's measurement of the force during impact.

Crook [8] attached his specimen to a long lead bar suspended horizontally, with a piezo-electric crystal between the specimen and the bar. A freely swinging ball or cylinder was used as the hammer to produce impact. The relative approach of the hammer and the specimen during the impact process was calculated on the basis of the elementary theory of elastic waves in a long slender bar. At the same time Crook derived a relation between impact force, relative approach, and time of contact during impact in the following way: he presumed that the impact process starts with a rigid perfectly-plastic action, thus making the force between the two bodies during their approach proportional to the area of contact; that the
approach stops when the maximum impact force is reached; and that immediately thereafter the two bodies start to move apart elastically under an action obeying Hertz' theory. Crook's analysis provides relations between impact force, relative approach, and time of contact, which agree closely with experimental values. He concludes that the assumption of perfectly plastic action with a constant yield pressure holds closely up to the instant when the maximum force of impact is attained. The value of the mean pressure $P_D$ occurring at the moment of the maximum impact force is very close to that of $P_d$ predicted on the basis of Tabor's theory. As a result, the use of $P_d$ for the mean pressure existing between bodies in collision seems justified. However, a comparison of theoretical and experimental curves of impact force against time reveals that further plastic flow exists even after the maximum impact force is reached and before elastic rebound occurs. Obviously, this final plastic flow does not occur under constant pressure. Therefore, Tabor's suggestion that viscous effects account for the difference between the values of $P_d$ and $P_r$ seems doubtful to Crook. He points out that the mean pressure between the colliding bodies remains nearly constant over a considerable portion of the impact process, i.e. does not vary with the strain rate, which is decreasing. Accordingly, $P_d$ cannot be strongly sensitive to viscous effects. On the other hand it seems evident from Crook's results that Tabor's $P_d$ provides an accurate prediction of the dynamic yield pressure; the meaning of $P_r$ is perhaps less clear. The fact remains, however, that the ratio $P_d/P_r$ increases for softer metals
and, as the present experiments show, is greater at higher temperatures. These results are consistent with Tabor's explanation based on time effects.

(4) Dimensional analysis.

In the hope of gaining greater insight into the impact process, dimensional analysis was employed and the results compared to experimental values.

For a small hard ball dropping on a massive specimen one can take as dependent variables the coefficient of restitution, \( e \), the indentation diameter, \( d \), and the impact time, \( t \). These depend on the mass \( m \) and diameter \( D \) of the indenting ball, as well as on its impact velocity \( v_i \). In addition, they depend on the properties of the specimen material, in particular on its Young's modulus \( E \) and on the yield stress. For the latter, one can use some nominal yield stress, e.g. the static yield stress \( \sigma_y \). The fact that the yield stress, and perhaps even the Young's modulus, are influenced by other quantities, such as strain rate, is presumed taken into account by the inclusion of the impact velocity among the independent variables. There are, of course, other factors which influence results but for the purposes of dimensional analysis the number of variables was limited to the above. The temperature of the specimen is presumed to affect only the Young's modulus and the yield stress, but not otherwise to enter into the problem.
If one considers first the indentation diameter \( d \) together with all the above independent variables, it may be shown that there exist a total of three independent dimensionless products which can be formed with these variables, namely

\[
\frac{d}{D}; \quad \frac{m v_1}{E D^3}; \quad \text{and} \quad \frac{\sigma_y}{E}
\]

On the basis of experimental results, \( d \) is known to be proportional to \( v^\alpha \) where \( \alpha \) is constant, so that the relation between these products is

\[
d = f_1 \left( \frac{\sigma_y}{E} \right) \left[ \frac{m v_1^2}{E D^3} \right]^{\alpha/2}
\]

where \( f_1(\sigma_y/E) \) remains unknown.

A similar analysis can be made by considering the time of impact, \( t \), along with the five independent variables to obtain the three dimensionless products

\[
\frac{t^2 DE}{m}; \quad \frac{m v_1^2}{ED^3}; \quad \text{and} \quad \frac{\sigma_y}{E}
\]

Since \( t \) is proportional to \( v_1^\beta \) where \( \beta \) is another constant one forms

\[
\left[ \frac{t^2 DE}{m} \right]^{1/2} = f_2 \left( \frac{\sigma_y}{E} \right) \left[ \frac{m v_1^2}{ED^3} \right]^{\beta/2}
\]

in which \( f_2(\sigma_y/E) \) is unknown. As will be seen below in Sections V. (2), the Equations (4) and (5) are in agreement with the test results.
A similar relation can be established between the coefficient of restitution and the five independent variables. It was found, however, that this relation failed to fit completely the experimental data, although at high velocities it is true that $e$ is proportional to $v_1^\gamma$ where $\gamma$ depends on the independent variables (other than $v_1$) and on temperature. One must conclude that other variables than those considered also influence the coefficient of restitution.

(5) Delay time of plastic deformation.

A number of investigators, in particular Clark and Wood [16], have observed a delay in the initiation of plastic deformation under rapid loading conditions. These observations were made for simple tension tests with a material possessing a relatively definite yield stress. The results indicate that the delay time depends on the level of the applied stress. It might seem, at first, that this phenomenon could also be studied by performing impact tests at very low velocities. However, Davies [9] found that an impact velocity of less than approximately 27 cm/sec is necessary for an entirely elastic impact in steel. This means that for steel the delay time is less than the contact time if the latter is greater than that produced by a 27 cm/sec impact velocity. With lead and aluminum it can be expected that some plastic deformation will occur at even lower velocities. The fact that a coefficient of restitution of unity could not be obtained for these two materials with the present set-up indicates that the delay time was
always less than the contact time for the stress levels encountered.

(6) Prediction of total time of contact between ball and specimen during impact.

The total time of contact between the ball and the specimen is of importance since it is needed in calculating strain rates and in estimating the delay time of plastic flow. This time of contact was measured experimentally; but it is also useful to arrive at an estimate through a simple analysis of the contact process.

The total time of contact \( t \) was estimated from the relation

\[
t = t_p + t_e
\]

where \( t_p \) and \( t_e \) were calculated as follows. The quantity \( t_p \) is the time necessary to decelerate the ball from the impact velocity \( v_1 \) to a velocity equal in magnitude to the rebound velocity \( v_2 \) but directed down. For this computation the ball was taken as rigid and the specimen as rigid-perfectly plastic with a yield pressure \( P_d \) given by Equation (2). An integration of the equation of motion for the ball gives

\[
t_p = \sqrt{\frac{m}{2m_1 P_d}} \cos^{-1} e
\]

where \( e \) is the coefficient of restitution, and \( r_1 \) and \( m \), respectively, the radius and mass of the ball. According to this equation \( t_p \) is zero for an elastic collision and is
equal to

\[ \frac{\pi}{2} \sqrt{2m} \frac{m}{r_1 f_d} \]

for a completely inelastic one. This last expression was originally derived by Tabor for impact with a rigid-perfectly plastic specimen [7]. The remaining time of contact, \( t_e \), is taken as twice the time of rebound, and rebound is presumed to start immediately after the ball reaches its maximum contact area with the specimen. In the rebound process the ball is forced to move away from the specimen by the elastic action of both ball and specimen. Finally, separation occurs at the velocity \( v_2 \) leaving a permanent indentation of radius \( r_2 \) greater than the radius of the ball \( r_1 \). According to Hertz

\[ t_e = 2.86 \frac{m^{2/5}}{r_1} \left[ \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \right]^{2/5} \left[ \frac{1}{r_1} \frac{1}{r_2} \right]^{1/5} v_2 \quad (8) \]

In this expression \( \left[ \frac{1}{r_1} \frac{1}{r_2} \right] \) can be calculated from the diameter of the permanent indentation \( d \) by

\[ \frac{1}{r_1} - \frac{1}{r_2} = \frac{3\pi}{d} \frac{p_r}{d} \left[ \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \right] \]

where \( p_r \) is given by Equation (3). However, if no permanent indentation is left then, according to Equation (7), \( t_p \) vanishes, and hence the total time of contact is given by Equation (8) with \( 1/r_2 \) equal to zero and with \( v_2 = v_1 \).
III. **Technique used in Present Experiments.**

In the present tests, bearing balls were dropped on a cylindrical specimen shaped as shown in Figure 1. Solid steel balls of 1" and 1/2" diameter were used, as well as 2017 aluminum alloy balls of 1" diameter either solid or lead-filled. The lead-filled balls were made by drilling a 1/2" hole through the center of the ball and filling it with lead. The specimens on which the balls were dropped were 10" long and 6" in diameter. They were made of either of two materials: commercially pure lead and an aluminum alloy (6061-T6). Specimens of the latter material were tested both in the as-rolled condition and also after annealing at 900°F for 3 hours. The serrations cut into the outer surface and the inclinations of these surfaces were intended to minimize the effect on the impact process of reflected waves. Care was taken that the specimen's top surface, on which the ball impinged, was always a freshly machined surface. In addition, the balls were dropped only in the neighborhood of the center of this surface at points relatively far apart from one another.

For the tests at elevated temperatures, the specimens were heated by placing them within a cylindrical oven provided with a cover which could be opened and closed rapidly for each test. The temperature distribution was measured by means of thermocouples imbedded at various points throughout the specimen, thus ensuring uniformity of temperature over the testing surface and beneath it.
Two techniques were used in the tests. For high velocities of impact (> 200 cm/sec) the ball was allowed to drop freely onto the horizontal surface of the specimen. For velocities less than 200 cm/sec, the ball was suspended by four fine threads and allowed to swing as a pendulum striking the specimen which now was placed with its axis horizontal.

In the free fall experiments the ball was held in place above the specimen by means of a small electromagnet. It was released by throwing a switch which reversed the electric current in the coil to just such an extent as to overcome the residual magnetism. To avoid giving the ball an angular impulse on releasing it the tip of the magnetic core from which it hung was spherical so contact was at only one point. Impact velocity was calculated simply from the height of drop, \( h_1 \). Rebound velocity, similarly, was found from the rebound height, \( h_2 \), as determined photographically (see for example Figure 2). In order to prevent the ball from striking twice in the same spot, the surface of the specimen was tilted at about 1° from the horizontal. This made it easier also to determine accurately the height of rebound. The coefficient of restitution, \( e \), defined as the ratio of rebound velocity to impact velocity was evaluated using the relation

\[
e = \frac{h_2}{h_1}
\]

Measurements also were made of the time of impact. For these
tests a fine constantan wire \((D = .003")\) was attached to the ball and the time of electrical contact between ball and specimen was measured by means of a high speed electronic counter.

In the low velocity impact tests, the ball was suspended in a four-threaded pendulum about 184 cm. long. It was held between two thin aluminum plates to which the threads were attached (Figure 3). Care was taken that the center of mass of the ball lie on a line with the directions of the threads and also that the impact occur at the lowest point in the path of travel of the ball. The release for the ball consisted simply of a very short silk thread held between knife edges which were parted suddenly. Measurements of time of impact were made with the same technique as in the free fall test, whereas the impact and rebound velocities were found from the rate at which the ball in its travel interrupted a thin horizontal slit of light. This latter measurement involved the use of a photocell and an oscilloscope. Figure 4 shows a typical photograph.

IV. Presentation of Results.

The test results are presented in Tables 1-9. The time of contact during impact, \(t\), is a measured quantity; the indentation diameter, \(d\), is an average of four measurements made with a microscope. When the impact velocity is under 200 cm/sec. the velocity of impact and the coefficient of restitution, \(e\), are measured quantities. For tests above 200 cm/sec. measured
quantities are height of drop $h_1$ and height of rebound $h_2$ from which the velocity of impact and the coefficient of restitution are calculated.

Results with different indenters are similar in nature so that they need not all be presented graphically. Figures 5-9 show the variation of $e$, $t$ and $d$ with impact velocity $v_1$ for a 1" steel ball striking in turn specimens of lead, annealed aluminum and as-rolled aluminum. One observes that as the velocity decreases the coefficient of restitution and the time of impact increase, while the size of the indentation decreases. Results of this kind have already been obtained by others [3,6] and indicate, among other things, that the impact process is more nearly elastic at lower velocities. An increase in temperature presumably decreases both the yield stress and the Young's modulus of the material and, hence decreases the coefficient of restitution and increases the impact area. The influence of temperature on time of contact is harder to predict. According to Tabor, in a rigid-perfectly plastic impact an increase in temperature increases the contact time. This conclusion is in qualitative agreement with present results which, however, show some scatter particularly at lower velocities.

The changes in the measured quantities for lead and the annealed aluminum alloy with temperature seem small if one remembers that the melting points for these materials are respectively $621^\circ F$ and $1200^\circ F$ (Figures 5-7). A relatively
temperatures (Figures 10-15). Since \( d/D \) differs from test to test, its value is indicated next to each point in question. All results seem to fall on one curve, with a minimum of scatter, irrespective of the size or material of the indenting ball. However, the curve shows not only the dependence of \( P_d \) on strain rate (\( d/tD \)) but also its dependence on strain (\( d/D \)), since the value of \( d/D \) varies along the curve and tends to decrease at lower strain rates. (A plot of results showing \( P_d \) versus \( d/D \) illustrates this point more clearly.) In Figures 10-15 the intercept with the vertical axis gives the value of \( P_d \) corresponding to zero strain rate at a small strain. This value of \( P_d \) can be interpreted in terms of the static yield stress through the relation

\[
\sigma_y = \frac{P_d}{2.8}
\]

which was derived empirically by Tabor [7] on the basis of static tests and which also has received some theoretical confirmation from the work of Ishlinsky [17] and from the analyses of the punch problem by Hencky [18] and by Shield and Drucker [19]. Table 11 shows a comparison between values of yield stress so obtained and the virgin yield of the material as measured in a simple compression test. Agreement is good in all cases except for the annealed aluminum alloy at 900\(^\circ\)F. This result suggests the possibility that \( P_d \) can by proper interpretation give a measure of the dynamic yield stress of the material at a given strain and a given strain rate. Work along these lines is continuing.
(2) Results based on dimensional analysis.

Equation (4), derived above on the basis of dimensional analysis, may be repeated here for convenience:

$$\frac{d}{D} = f_1 \left(\frac{\sigma}{E}\right) \left[\frac{m}{ED^3} \left(\frac{v_1}{E}\right)^{2a/2}\right]$$

Measurements of the indentation diameter at various impact velocities indicate that $\alpha$ is approximately 0.45. The fact that $d$ depends on $v_1$ had already been found by Schneider [20] and others for materials at room temperature, and present results indicate that this holds irrespective of temperature for lead and aluminum (Figure 16). It appears also that the numerical value of $\alpha$ does not depend on the size or material of the indenting ball and only slightly on specimen material (Table 12).

The validity of Equation (4) was examined experimentally by varying one at a time the parameters in the equation. The ball diameter, $D$, was the first to be changed. Specimens were tested with balls of different diameters at a number of temperatures and impact velocities. Next, the dependence on the mass $m$ of the ball was examined by changing the material of the indenter, first from steel to aluminum and then from solid aluminum to lead-filled aluminum. In each case the tests were run at a number of temperatures and impact velocities. The results consistently show strong agreement with values predicted on the basis of Equation (4), which thus appears of value in predicting the indentation diameter in impact tests.
One must add that the function \( f_1(\sigma_y/E) \) remains undetermined, although according to Table 12, its numerical value does not depart greatly from 4.5.

Dimensional analysis also gives an equation for the total time of impact, namely

\[
\left[ \frac{t^2}{\frac{DEB}{m}} \right]^{1/2} = f_2 \left( \frac{\sigma_y}{E} \right) \left[ \frac{m v_1^2}{ED^3} \right]^{3/2}
\]

according to which \( t \) is proportional to \( v_1^8 \) where \( \beta \) is a new constant. This relation is in agreement with the present results for which \( \beta \approx -0.15 \), irrespective of temperature, indenter material or specimen material. However, rather than presenting a graph showing the variation of \( t \) with \( v_1 \), it is more interesting to make use of Equation (4) as well and instead plot \( d/t \) against \( v_1 \). Typical values are shown in Figure 17. It may be noted that for each material and using one indenter all points fall on one line no matter what the temperature. The dependence of \( t \) on \( D \) and on \( m \) was examined by varying each of these parameters independently. Results show strong agreement with predictions based on Equation (5). The values of \( f_2(\sigma_y/E) \) given in Table 12 are near 5, but the variation in \( f_2(\sigma_y/E) \) is greater than that of \( f_1(\sigma_y/E) \).

One should note how closely the above results, which are based on dimensional analysis, compare to results based on a simple physical analysis of the impact process. For
instance, for elastic impact Hertz' theory yields

\[ d = 1.5 \left\{ \left[ \frac{1-\nu_1}{E_1} + \frac{1-\nu_2}{E_2} \right]^2 - \frac{1}{2} \right\}^{1/5} \left( \frac{D}{m v_1} \right)^{2/5} \]

\[ t = 3.29 \left\{ \left[ \frac{1-\nu_1}{E_1} + \frac{1-\nu_2}{E_2} \right]^2 - \frac{1}{2} \right\}^{1/5} \left( \frac{D}{m v_1} \right)^{1/5} \]

which corresponds to \( \alpha = 0.40 \) and \( \beta = -0.20 \). At the other extreme, for rigid-perfectly plastic impact, according to Tabor's analysis,

\[ d = 2 \left( \frac{Dm}{n^2} \right)^{1/4} v_1^{1/2} \]

\[ t = \frac{n}{2} \sqrt{\frac{m}{D}} \]

yielding values of \( \alpha = 0.50 \) and \( \beta = 0 \). It is interesting to note that experimental values of \( \alpha \) and \( \beta \) lie, respectively, between the two values predicted by these simple analyses. (Actually, the experimental values of \( \alpha \) and \( \beta \) vary somewhat with impact velocity tending more toward the perfectly plastic values as the impact velocity is increased.) Equations (4) and (5) predict values of \( d \) and \( t \) which agree quite closely with experimental results for either lead or the aluminum alloy at any temperature. This would seem to indicate that viscous effects, if present, influence the impact process mainly through the properties of the materials, i.e. through the functions \( f_1(\sigma_y/E) \) and \( f_2(\sigma_y/E) \).
(3) Approximation for the total time of impact.

Approximate values of the total time of impact were calculated on the basis of Equation (6) using the present test results. In the calculations \( P_d \) and \( P_r \) are given, respectively, by Equations (2) and (3). The values of \( E_1 \) and \( E_2 \) are taken from Table 13 and Poisson's ratio was set equal to 0.3 for both ball and specimen. Figures 18 and 19 show typical results. In general, the difference between calculated and experimental values is less than 10% for lead and 15% for aluminum over the entire range of velocities. Apparently, therefore, Equation (6) gives a good estimate of the total time of impact for this velocity range.

(4) The yield pressure as evaluated by \( P_r \) or \( P_d \); meaning of \( P_d/Pr \).

One important result of the hardness test is a measure of yield pressure. As mentioned in section II.(2) and depending on the analysis, Tabor obtains two different expressions for yield pressure, viz. \( P_d \) and \( P_r \). It is of interest to contrast these two quantities to see which gives more reliable information on the yield properties of the specimen. Such a comparison already was made both by Tabor [7] and by Crock [8]. However, some additional comments based on present results may be of value.

Equation (3) gives the quantity \( P_r \) as derived by Tabor from the rebound height. Since it is based on Hertz' theory
of elastic contact, $P_r$ will be sensitive to the properties of both the indenter and the specimen. Experimental results confirm this sensitivity to indenter properties (Table 14). Therefore, comparisons of test results obtained with different types of indenters cannot be made directly.

In contrast, $P_d$ is obtained by equating the loss in kinetic energy to the energy required to produce the indentation. It appears from present results, as given in section V.(1) that $P_d$ is largely independent of the properties of the indenter, i.e. depends almost exclusively on the specimen properties. Moreover, in Crook's experiments the value of $P_d$ was close to the value of the mean yield pressure at the moment when the impact force reaches its maximum value as given by direct measurement of impact force. It would thus seem that $P_d$ furnishes a more reliable measure of specimen properties than does $P_r$.

According to Tabor's explanation, $P_r$ gives the magnitude of the yield pressure at the end of plastic action (i.e. at the start of elastic recovery) and $P_d$ gives the average value of the yield pressure for the entire plastic process. Tabor argues that when viscous effects are present, $P_d$ will be greater than $P_r$ because the strain rates are greater during the plastic process than they are at the start of elastic recovery. Consequently, the ratio $P_d/P_r$ has a value greater than unity and a higher value for softer materials. Present results do not make Tabor's explanation any less valid. The
ratio $\frac{P_d}{P_r}$ was found greater than unity in all cases. 
(The one exception is for tests at low velocities with a 1" lead filled 2017 aluminum alloy ball. In this case the high values of $P_r$ may well be explained by the dependence of $P_r$ on the properties of the indenter, i.e. on the spring-like action of the aluminum surrounding the lead core). The present experiments also show that $\frac{P_d}{P_r}$ is higher for specimens of lead than for those of aluminum alloy and, moreover, is greater the higher the temperature.

(5) The influence of temperature.

As expected, for the same impact velocity the coefficient of restitution, $e$, decreases with an increase in temperature (e.g. Fig. 5 and Table 1). This is apparently due in part to a decrease in both the Young's modulus and the yield pressure of the material, as evidenced by the drop in the values of $P_d$ and $P_r$. In addition, the ratio $\frac{P_d}{P_r}$ is greater at more elevated temperature. This is in line with Tabor's theory since an increase in temperature undoubtedly produces an increase in the viscosity of the materials.

The fact that the values of $P_d$, $e$ and $\frac{P_d}{P_r}$ for an annealed aluminum alloy specimen at high temperature tend to those of lead at room temperature (Figures 10-15, 5,6, Table 15) would seem to suggest that by choosing an appropriate temperature the two materials will have a similar behavior. However, for the temperature range covered in these experiments
(70° to 900°F for annealed aluminum alloy, 70°F to 450°F for lead) the corresponding changes in the properties of the two materials are small in comparison to the difference in their properties at room temperature. This is in spite of the fact that the above temperature ranges are quite large (the melting points of the materials are respectively about 1200°F and 600°F).

Conclusions

The principal conclusions one can draw on the basis of this investigation bear more directly on the impact test as such than on the general behavior of materials. For the bouncing ball test, dimensional analysis yields two relations namely

\[
\frac{d}{D} = f_1 \left( \frac{\sigma}{E} \right) \left[ \frac{m v^2}{E D^3} \right]^{2/3}
\]

and

\[
\left[ \frac{L^2 D^2}{m} \right]^{1/2} = f_2 \left( \frac{\sigma}{E} \right) \left[ \frac{m v^2}{E D^3} \right]^{2/3}
\]

which predict quite accurately for any temperature the dependence of the indentation diameter and the time of contact during impact on the mass, diameter, and velocity of the ball.

Experimental results indicate that \( \alpha = 0.45 \) and \( \beta = 0.15 \). These values compare to \( \alpha = 0.40 \) and \( \beta = 0.20 \) obtained from a simple analysis assuming elastic impact, and to \( \alpha = 0.50 \) and \( \beta = 0 \) for a perfectly plastic impact. Furthermore, although the experimental values of \( \alpha \) and \( \beta \) are not very sensitive
to changes in impact velocity they do tend toward the elastic values as the velocity is decreased.

On the other hand, the results of dimensional analysis give no clue to the form of the functions $f_1(\sigma_y/E)$ and $f_2(\sigma_y/E)$ except that numerical values of these functions vary little with temperature.

In regard to Tabor's expressions $P_d$ and $P_r$ for the dynamic yield pressure, our results do not contradict Tabor's understanding of these quantities. On the basis of his experiments using specimens of different materials, Tabor concluded that the ratio $P_d/P_r$ is greater for those materials whose stress-strain relation is more strongly time dependent. Present results appear to be consistent with this conclusion, in that, for a given material, this ratio is greater at higher temperatures where one would expect viscous effects to be more pronounced. Our results also show that for any given material the value of $P_d$ changes with impact velocity presumably varying with the strain and the strain rate. This result does not agree with the supposition made by previous investigators that $P_d$ remains constant throughout the impact process. It is, however, not inconsistent with Tabor's interpretation of the ratio $P_d/P_r$.

The total time of contact during impact was measured for the lead and aluminum specimens at different temperatures. The results are presented in the text and compare closely to
values derived on the basis of the simple analysis of the contact process presented in section II.(6) above.

Results of impact tests using a bouncing ball are difficult to interpret in terms applicable to a more general understanding of the behavior of materials. However, it appears that the static yield stress can be obtained by an extrapolation of present results involving the dynamic yield pressure $P_d$ to a zero strain rate. This suggests the possibility that the dynamic yield stress at various strain rates can also be measured with a bouncing ball; work in this direction is continuing.

One can look at the results also by plotting the coefficient of restitution against impact velocity. As expected, this coefficient increases at lower velocities where a greater proportion of the kinetic energy of impact is recovered. It might be supposed that for values of the velocity beneath a certain critical value, the coefficient of restitution would equal unity. This critical velocity could then be used as a measure of the limit of elastic action and, perhaps, as a reference point which would allow comparisons between the behavior of different metals at different temperatures. Unfortunately, as both Davies and Raman found already, the critical velocity is so low that it barely can be attained in a simple experiment even at room temperature.
Bibliography


Bibliography (Cont.)


### TABLE 1

Results obtained with 1" Steel Ball striking Lead Specimen

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### TABLE 3

Results obtained with 1" Steel Ball striking As-rolled Specimen of 6061-T6 Aluminum

<table>
<thead>
<tr>
<th>Impact Velocity $v_1$ (cm/sec)</th>
<th>Coeff. of Restitution $e$</th>
<th>Impact Time, $t$ $(10^{-4}$ sec)</th>
<th>Indentation Diameter $d$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temperature</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3.01</td>
<td>0.981</td>
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</tr>
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<td>0.980</td>
<td>2.52</td>
<td>--</td>
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<td>0.096</td>
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<td>0.689</td>
<td>1.21</td>
<td>0.166</td>
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<td>0.252</td>
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### TABLE 4

Results obtained with 1/2" Steel Ball striking Lead Specimen

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<th>Impact Velocity $v_1$ (cm/sec)</th>
<th>Impact Height $h_1$ (cm)</th>
<th>Rebound Height $h_2$ (cm)</th>
<th>Coeff. of Restitution $e$ (10$^{-4}$ sec)</th>
<th>Impact Time, $t$ (10$^{-4}$ sec)</th>
<th>Indentation Diameter $d$ (cm)</th>
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<tr>
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<td>0.125</td>
<td>--</td>
<td>0.264</td>
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<td>313</td>
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<td>0.308</td>
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<td>313</td>
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<td>0.70</td>
<td>0.118</td>
<td>--</td>
<td>0.313</td>
</tr>
<tr>
<td>313</td>
<td>50</td>
<td>0.70</td>
<td>0.118</td>
<td>--</td>
<td>0.313</td>
</tr>
<tr>
<td>524</td>
<td>140</td>
<td>1.70</td>
<td>0.11</td>
<td>1.37</td>
<td>0.390</td>
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<td>0.264</td>
<td>3.65</td>
<td>0.042</td>
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<td>0.217</td>
<td>2.22</td>
<td>0.106</td>
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<td></td>
<td></td>
<td>0.146</td>
<td>(2.69)</td>
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<tr>
<td>312</td>
<td>49.8</td>
<td>0.58</td>
<td>0.108</td>
<td>--</td>
<td>0.329</td>
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<tr>
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<td>0.100</td>
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<td>1.44</td>
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TABLE 5
Results obtained with 1/2" Steel Ball
striking Annealed Specimen 6061-T6 Aluminum

<table>
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<tr>
<th>Impact Velocity $v_1$ (cm/sec)</th>
<th>Impact Height $h_1$ (cm)</th>
<th>Rebound Height $h_2$ (cm)</th>
<th>Coeff. of Restitution $e$</th>
<th>Impact Time, $t$ ($10^{-4}$ sec)</th>
<th>Indentation Diameter $d$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temperature</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.01</td>
<td>0.717</td>
<td>1.58</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>30.2</td>
<td>0.426</td>
<td>0.89</td>
<td>0.071</td>
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<tr>
<td>94.7</td>
<td>0.41</td>
<td>0.72</td>
<td>0.118</td>
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<td></td>
</tr>
<tr>
<td>221</td>
<td>3.1</td>
<td>0.352</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>313</td>
<td>5.85</td>
<td>0.342</td>
<td>0.59</td>
<td>0.194</td>
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<tr>
<td>443</td>
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<td>0.324</td>
<td>0.56</td>
<td>0.227</td>
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<td>0.307</td>
<td>0.55</td>
<td>0.248</td>
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<td>524</td>
<td>12.8</td>
<td>0.302</td>
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<td>0.250</td>
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<td></td>
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<td>1.74</td>
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</tr>
<tr>
<td>31.5</td>
<td>0.367</td>
<td>0.94</td>
<td>0.071</td>
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</tr>
<tr>
<td>97.4</td>
<td>0.342</td>
<td>0.70</td>
<td>0.124</td>
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<tr>
<td>221</td>
<td>2.55</td>
<td>0.319</td>
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<td>0.176</td>
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<tr>
<td>312</td>
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<td>0.201</td>
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<tr>
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<td>0.294</td>
<td>0.60</td>
<td>0.244</td>
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<tr>
<td>524</td>
<td>10.50</td>
<td>0.273</td>
<td>0.58</td>
<td>0.266</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 6

Results obtained with 1" 2017 Aluminum Ball striking Lead Specimen

<table>
<thead>
<tr>
<th>Impact Velocity ( v_i ) (cm/sec)</th>
<th>Coeff. of Restitution ( e )</th>
<th>Impact Time, ( t ) (10^-4 sec)</th>
<th>Indentation Diameter ( d ) (cm)</th>
</tr>
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<tbody>
<tr>
<td>Room Temperature</td>
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</tr>
<tr>
<td>2.05 0.491 5.98 0.051</td>
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<td>12.7 0.379 2.80 0.113</td>
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</tr>
<tr>
<td>28.2 0.269 2.57 0.166</td>
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</tr>
<tr>
<td>46.3 0.234 2.24 0.216</td>
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</tr>
<tr>
<td>92.8 0.154 1.92 0.285</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Temperature = 300°F</td>
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<td></td>
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</tr>
<tr>
<td>2.87 0.308 5.00 -- 0.129</td>
<td></td>
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</tr>
<tr>
<td>12.8 0.208 2.90 0.176</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>25.8 0.216 2.70 0.232</td>
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<tr>
<td>46.4 0.193 2.51 0.311</td>
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</tr>
<tr>
<td>89.5 0.073 2.62 0.315</td>
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<td></td>
</tr>
<tr>
<td>Temperature = 450°F</td>
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</tr>
<tr>
<td>3.62 0.210 4.90 0.071</td>
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<tr>
<td>13.2 0.210 3.25 0.132</td>
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</tr>
<tr>
<td>29.0 0.193 2.90 0.185</td>
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</tr>
<tr>
<td>44.4 0.173 2.51 0.226</td>
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<tr>
<td>92.2 0.124 2.20 0.315</td>
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TABLE 7

Results obtained with 1" 2017 Aluminum Ball striking Annealed Specimen of 6061-T6 Aluminum

<table>
<thead>
<tr>
<th>Impact Velocity $v_1$ (cm/sec)</th>
<th>Coeff. of Restitution $e$</th>
<th>Impact Time, $t$ $(10^{-4}$ sec)</th>
<th>Indentation Diameter $d$ (cm)</th>
</tr>
</thead>
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<tr>
<td>Room Temperature</td>
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</tr>
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<td>2.64</td>
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<td>13.5</td>
<td>0.696</td>
<td>1.48</td>
<td>0.069</td>
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<td>0.101</td>
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</tr>
<tr>
<td>93.5</td>
<td>0.436</td>
<td>0.98</td>
<td>0.176</td>
</tr>
<tr>
<td>Temperature = 400°F</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>11.7</td>
<td>0.701</td>
<td>1.65</td>
<td>0.073</td>
</tr>
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<td>24.3</td>
<td>0.591</td>
<td>1.28</td>
<td>0.102</td>
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<td>43.1</td>
<td>0.471</td>
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<td>0.133</td>
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<td>90.6</td>
<td>0.335</td>
<td>1.01</td>
<td>0.186</td>
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<td></td>
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<tr>
<td>47.8</td>
<td>0.411</td>
<td>1.20</td>
<td>0.134</td>
</tr>
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<td>93.0</td>
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<td>1.12</td>
<td>0.194</td>
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TABLE 8

Results obtained with 1" 2017 Aluminum Lead Filled Ball striking Lead Specimen

<table>
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<tr>
<th>Impact Velocity $v_1$ (cm/sec)</th>
<th>Coeff. of Restitution $e$</th>
<th>Impact time, $t$ ($10^{-4}$ sec)</th>
<th>Indentation Diameter $d$ (cm)</th>
</tr>
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<tr>
<td>Room Temperature</td>
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<td>2.32 0.469 5.44 0.066</td>
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</tr>
<tr>
<td>Temperature = 300°F</td>
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</tr>
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<td>10.9 0.263 -- 0.147</td>
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<td>48.4 0.240 3.31 0.269</td>
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<td>90 0.230 3.14 0.364</td>
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<td></td>
</tr>
<tr>
<td>Temperature = 450°F</td>
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</tr>
<tr>
<td>3.58 0.235 4.73 --</td>
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<tr>
<td>11.7 0.234 3.92 0.144</td>
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<td>26.2 0.217 3.81 0.213</td>
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<td>93.0 0.211 3.06 0.373</td>
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</table>
TABLE 9
Results obtained with 1" 2017 Aluminum Lead Filled Ball striking Annealed Specimen of 6061-T6 Aluminum

<table>
<thead>
<tr>
<th>Impact Velocity (v_1) (cm/sec)</th>
<th>Coeff. of Restitution (e)</th>
<th>Impact Time, (t) ((10^{-4}) sec)</th>
<th>Indentation Diameter (d) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room Temperature</td>
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</tr>
<tr>
<td>2.16</td>
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<td>0.131</td>
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<td>0.696</td>
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<td>0.113</td>
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<td>40.3</td>
<td>0.595</td>
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<td>0.141</td>
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<tr>
<td>93.5</td>
<td>0.63</td>
<td>1.31</td>
<td>0.208</td>
</tr>
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<td></td>
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<tr>
<td>2.97</td>
<td>0.780</td>
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<td>0.700</td>
<td>1.98</td>
<td>0.131</td>
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<td>0.119</td>
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<td>0.154</td>
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<td>0.562</td>
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<td>0.213</td>
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</tr>
<tr>
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<td>0.565</td>
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<td>0.167</td>
</tr>
<tr>
<td>93.0</td>
<td>--</td>
<td>1.50</td>
<td>0.232</td>
</tr>
<tr>
<td>Material</td>
<td>Temp.</td>
<td>Indenting Ball</td>
<td>d/D</td>
</tr>
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<td>--------</td>
<td>----------------</td>
<td>-----</td>
</tr>
<tr>
<td>Lead</td>
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<td>0.313</td>
</tr>
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<td>½&quot; steel</td>
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<tr>
<td></td>
<td>300°F</td>
<td>1&quot; steel</td>
<td>0.329</td>
</tr>
<tr>
<td></td>
<td></td>
<td>½&quot; steel</td>
<td>0.328</td>
</tr>
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<td>Aluminum</td>
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</tr>
<tr>
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<td>400°F</td>
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<td>0.215</td>
</tr>
<tr>
<td></td>
<td></td>
<td>½&quot; steel</td>
<td>0.210</td>
</tr>
</tbody>
</table>
**TABLE 11**

Static Yield Stress

(This table compares values of the static yield stress as obtained through an extrapolation of present impact test results to values found in simple compression and simple tension tests.)

<table>
<thead>
<tr>
<th>Specimen: Lead</th>
<th>Source</th>
<th>70°F</th>
<th>300°F</th>
<th>450°F</th>
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<td></td>
<td>Present Impact Tests</td>
<td>800 psi</td>
<td>710 psi</td>
<td>650 psi</td>
</tr>
<tr>
<td>Static Compression Test (0.2% Offset)</td>
<td>850 psi</td>
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<th>Specimen: Annealed 6061-T6 Aluminum</th>
<th>Source</th>
<th>70°F</th>
<th>400°F</th>
<th>900°F</th>
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<tr>
<td>Present Impact Tests</td>
<td>8,500 psi</td>
<td>7,000 psi</td>
<td>3,400 psi</td>
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<tr>
<td>Static Tension Tests (0.2% Offset)</td>
<td>8,000 psi</td>
<td>6,500 psi</td>
<td>less than 2,000 psi</td>
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<th>Specimen: As-rolled 6061-T6 Aluminum</th>
<th>Source</th>
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<th>400°F</th>
<th>900°F</th>
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<tr>
<td>Present Impact Tests</td>
<td>36,000 psi</td>
<td>28,000 psi</td>
<td>3,000 psi</td>
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<tr>
<td>Static Tension Tests (0.2% Offset)</td>
<td>40,000 psi</td>
<td>29,000 psi</td>
<td>less than 3,000 psi</td>
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* Data furnished by Alcoa Research Laboratory.
<table>
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<tr>
<th>Indenting Ball</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$f_1 (\sigma_y/E)$ *</th>
<th>$f_2 (\sigma_y/E)$ *</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70°F</td>
<td>300°F</td>
<td>450°F</td>
<td>70°F</td>
</tr>
<tr>
<td>1&quot; steel</td>
<td>0.44</td>
<td>0.45</td>
<td>0.45</td>
<td>-0.14</td>
</tr>
<tr>
<td>$\frac{1}{2}$&quot; steel</td>
<td>0.44</td>
<td>0.44</td>
<td></td>
<td>-0.15</td>
</tr>
<tr>
<td>1&quot; 2017 Aluminum</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>-0.18</td>
</tr>
<tr>
<td>1&quot; 2017 Aluminum</td>
<td>0.46</td>
<td>0.45</td>
<td>0.46</td>
<td>-0.18</td>
</tr>
<tr>
<td>Lead Filled</td>
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<td>70°F</td>
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<tr>
<td>1&quot; steel</td>
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<td>$\frac{1}{2}$&quot; steel</td>
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<tr>
<td>1&quot; 2017 Aluminum</td>
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<tr>
<td>Lead Filled</td>
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* Computed with Young's Moduli given in Table 13.
TABLE 13
Values of Young's Moduli \(\left(10^{11} \text{ dynes/cm}^2\right)\) used in Calculations

<table>
<thead>
<tr>
<th>Temperature Material</th>
<th>70°F</th>
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<tr>
<td>Lead*</td>
<td>1.6</td>
<td>1.3</td>
<td>1.2</td>
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<tr>
<td>6061 Aluminum**</td>
<td>7.0</td>
<td></td>
<td>6.0</td>
<td>2.9</td>
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<tr>
<td>Steel</td>
<td>20</td>
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** Alcoa Research Laboratory.
TABLE 14
Dependence of $P_r$ on Indenter Properties
(Room Temperature Tests)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$d/D$</th>
<th>$P_r$</th>
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<tr>
<td></td>
<td></td>
<td>1&quot; steel ball</td>
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<tr>
<td></td>
<td></td>
<td>1/2&quot; steel ball</td>
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<tr>
<td></td>
<td></td>
<td>1&quot; 2017 aluminum ball</td>
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<tr>
<td></td>
<td></td>
<td>1&quot; 2017 alum. lead filled ball</td>
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<tr>
<td>Lead</td>
<td>0.11</td>
<td>$3.2 \times 10^3$ psi</td>
</tr>
<tr>
<td>Annealed 6061-T6 aluminum</td>
<td>0.07</td>
<td>$29 \times 10^3$ psi</td>
</tr>
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</table>

In computing values of $P_r$, $v_1 = v_2 = 0.3$, while $E_1$ and $E_2$ are taken from Table 13.

TABLE 15
Dependence of $P_d/P_r$ on Temperature
(Indenter: 1" Steel Ball)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$d$</th>
<th>$P_d/P_r$</th>
</tr>
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<tr>
<td></td>
<td></td>
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<td>Lead</td>
<td>0.31</td>
<td>2.0</td>
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<td>Annealed 6061-T6 aluminum</td>
<td>0.23</td>
<td>1.24</td>
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<td>As-rolled 6061-T6 aluminum</td>
<td>0.08</td>
<td>1.17</td>
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FIG. 1 SKETCH OF SPECIMEN
Figure 2. Ball in free fall bouncing from specimen surface. (Photograph is of 1" steel ball striking annealed specimen of 061-T6 aluminum at 443 cm/sec. Height of rebound = 7.6 cm.)
FIG. 3      SUSPENSION SYSTEM FOR INDENTING BALL
Figure 4. Oscilloscope pattern showing travel of ball suspended as a simple pendulum. (Time scale is horizontal: 20 divisions = 1 second. Ball approaches from the left. Distance from specimen is indicated by the two heavy horizontal lines: the top line is 10 mm. and the bottom 1 mm. away from the specimen.)
FIG. 5 COEFFICIENT OF RESTITUTION AND IMPACT TIME FOR 1" STEEL BALL STRIKING LEAD SPECIMEN

TEMPERATURE
- 70°F
- 300°F
- 450°F

IMPACT TIME

COEFFICIENT OF RESTITUTION

IMPACT VELOCITY, vi, cm/sec

0
10
20
30
40
50
60

0
100
200
300
400
500
600
FIG. 7 DIAMETER OF IDENTATION PRODUCED WITH 1" STEEL BALL
FIG. 8 COEFFICIENT OF RESTITUTION AND IMPACT TIME FOR 1" STEEL BALL STRIKING AS ROLLED SPECIMEN OF 6061-T6 ALUMINUM
FIG. 9 INDENTATION DIAMETER FOR 1" STEEL BALL STRIKING AS ROLLED SPECIMEN OF 6061-T6 ALUMINUM
FIG. 10 DEPENDENCE OF $P_d$ ON $\frac{d}{1D}$ FOR LEAD SPECIMEN AT ROOM TEMPERATURE

NOTE: NUMBERS ON GRAPH INDICATE VALUE OF $d/D$ FOR EACH TEST
FIG. 11 DEPENDENCE OF $P_d$ ON $\frac{d}{f_D}$ FOR LEAD SPECIMEN AT 300°F
FIG. 12 DEPENDENCE OF $P_d$ ON $\frac{d}{tD}$ FOR LEAD SPECIMEN AT 450°F

NOTE: NUMBERS ON GRAPH INDICATE VALUE OF $d/D$ FOR EACH TEST

- ○ 1" STEEL BALL
- ▲ 1" 2017 ALUMINUM BALL
- ● 1" 2017 ALUMINUM LEAD FILLED BALL
FIG. 14 DEPENDENCE OF $P_d$ ON $\frac{d}{1D}$ FOR ANNEALED SPECIMEN OF 6061-T6 ALUMINUM AT 400°F

NOTE: NUMBERS ON GRAPH INDICATE VALUE OF $d/D$ FOR EACH TEST
FIG. 15 DEPENDENCE OF $P_d$ ON $\frac{d}{1D}$ FOR ANNEALED SPECIMEN OF 6061-T6 ALUMINUM AT 900°F

NOTE: NUMBERS ON GRAPH INDICATE VALUE OF $d/D$ FOR EACH TEST
FIG. 16 RELATION BETWEEN LOG d AND LOG v₁ (INDENTER IS 1" STEEL BALL)
FIG. 17 DEPENDENCE OF $d'/t$ ON IMPACT VELOCITY, $v_i$ (INDENTER IS 1" STEEL BALL)
FIG. 19 TOTAL TIME OF IMPACT FOR 1" STEEL BALL STRIKING ANNEALED SPECIMEN OF 6061-T6 ALUMINUM AT ROOM TEMPERATURE
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